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APPLICATION NO.	FILING DATE	FIRST NAMED INVENTOR	ATTORNEY DOCKET NO.	CONFIRMATION NO.
09/759,603	01/16/2001	Joerg Drescher	225/49512	9440

7590 02/10/2005

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EXAMINER	
HOGAN, MARY C	
ART UNIT	**PAPER NUMBER**
2123	

DATE MAILED: 02/10/2005

Please find below and/or attached an Office communication concerning this application or proceeding.

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Office Action Summary	Application No. 09/759,603	Applicant(s) DRESCHER ET AL.	
	Examiner Mary C Hogan	Art Unit 2123	

-- The MAILING DATE of this communication appears on the cover sheet with the correspondence address --

Period for Reply

A SHORTENED STATUTORY PERIOD FOR REPLY IS SET TO EXPIRE 3 MONTH(S) FROM THE MAILING DATE OF THIS COMMUNICATION.

- Extensions of time may be available under the provisions of 37 CFR 1.136(a). In no event, however, may a reply be timely filed after SIX (6) MONTHS from the mailing date of this communication.
- If the period for reply specified above is less than thirty (30) days, a reply within the statutory minimum of thirty (30) days will be considered timely.
- If NO period for reply is specified above, the maximum statutory period will apply and will expire SIX (6) MONTHS from the mailing date of this communication.
- Failure to reply within the set or extended period for reply will, by statute, cause the application to become ABANDONED (35 U.S.C. § 133). Any reply received by the Office later than three months after the mailing date of this communication, even if timely filed, may reduce any earned patent term adjustment. See 37 CFR 1.704(b).

Status

1)☒ Responsive to communication(s) filed on 313/01/.

2a)☐ This action is **FINAL**. 2b)☒ This action is non-final.

3)☐ Since this application is in condition for allowance except for formal matters, prosecution as to the merits is closed in accordance with the practice under *Ex parte Quayle*, 1935 C.D. 11, 453 O.G. 213.

Disposition of Claims

4)☒ Claim(s) 1-20 is/are pending in the application.

4a) Of the above claim(s) _____ is/are withdrawn from consideration.

5)☐ Claim(s) _____ is/are allowed.

6)☒ Claim(s) 1-20 is/are rejected.

7)☐ Claim(s) _____ is/are objected to.

8)☐ Claim(s) _____ are subject to restriction and/or election requirement.

Application Papers

9)☒ The specification is objected to by the Examiner.

10)☒ The drawing(s) filed on 16 January 2001 is/are: a)☒ accepted or b)☐ objected to by the Examiner.

Applicant may not request that any objection to the drawing(s) be held in abeyance. See 37 CFR 1.85(a).

Replacement drawing sheet(s) including the correction is required if the drawing(s) is objected to. See 37 CFR 1.121(d).

11)☐ The oath or declaration is objected to by the Examiner. Note the attached Office Action or form PTO-152.

Priority under 35 U.S.C. § 119

12)☒ Acknowledgment is made of a claim for foreign priority under 35 U.S.C. § 119(a)-(d) or (f).

a)☒ All b)☐ Some * c)☐ None of:

1.☒ Certified copies of the priority documents have been received.

2.☐ Certified copies of the priority documents have been received in Application No. _____.

3.☐ Copies of the certified copies of the priority documents have been received in this National Stage application from the International Bureau (PCT Rule 17.2(a)).

* See the attached detailed Office action for a list of the certified copies not received.

Attachment(s)

1) ☒ Notice of References Cited (PTO-892)

2) ☐ Notice of Draftsperson's Patent Drawing Review (PTO-948)

3) ☒ Information Disclosure Statement(s) (PTO-1449 or PTO/SB/08) Paper No(s)/Mail Date 6.

4) ☐ Interview Summary (PTO-413) Paper No(s)/Mail Date. _____ .

5) ☐ Notice of Informal Patent Application (PTO-152)

6) ☐ Other: _____.

DETAILED ACTION

1. This application has been examined.

2. **Claims 1-20** have been examined and rejected.

3. This is a resend of the Detailed Action sent out by the Office 7/29/04. The original Detailed Action was returned to the Office as "Undeliverable".

Priority

4. Receipt is acknowledged of papers submitted under 35 U.S.C. 119(a)-(d), which papers have been placed of record in the file, specifically, German Patent Application Number 100 01 484.4, filed 1/15/00.

Specification

5. The disclosure is objected to because of the following informalities. Appropriate correction is required.

6. The explanation of Figure 1, elements 6 and 7 are unclear as to whether each element individually contains a sensor and actuator model or weather element 6 contains a sensor model and element 7 contains an actuator model. Specifically, Page 9, line 36-Page 10, line 5 specify "sensor model 6" or an "actuator model 6,7" followed by "sensor/actuator models 6 and/or 7".

7. Page 10, line 29 and Page 12, line25, the spelling of "analogue" should be changed to "analog" for consistency with "analog/digital" as used throughout the specification.

8. Page 13, line 36-Page 14, line 1, "signal generator" should be associated with element 41 in Figure 3 and "temperature cell" should be associated with element 40 in Figure 3.

Claim Interpretation

9. **Claim 12** states "a subordinate regulating loop" and "fast regulation". It is unclear from the claims and the specification what a subordinate regulating loop and fast regulation are. This claim was interpreted to be directed to a feedback loop between the tested component and the drive model to provide variables to the drive model which in turn, create signals that drive the output stages of the signal interfaces.

Claim Rejections - 35 USC § 112

10. The following is a quotation of the second paragraph of 35 U.S.C. 112:

The specification shall conclude with one or more claims particularly pointing out and distinctly claiming the subject matter which the applicant regards as his invention.

11. **Claim 12** is rejected under 35 U.S.C. 112, second paragraph, as being indefinite for failing to particularly point out and distinctly claim the subject matter which applicant regards as the invention. The claim states "a subordinate regulating loop" and "fast regulation". It is unclear from the claims and the specification what a subordinate regulating loop and fast regulation are, making the claim vague and indefinite.

Claim Rejections - 35 USC § 102

12. The following is a quotation of the appropriate paragraphs of 35 U.S.C. 102 that form the basis for the rejections under this section made in this Office action:

A person shall be entitled to a patent unless –

(b) the invention was patented or described in a printed publication in this or a foreign country or in public use or on sale in this country, more than one year prior to the date of application for patent in the United States.

13. **Claims 1-20** are rejected under 35 U.S.C. 102(b) as being anticipated by Wagner et al (Wagner et al, "A Strategy to Verify Chassis Controller Software-Dynamics, Hardware and Automation", IEEE Transactions on Systems, Man, and Cybernetics-Part A: Systems and Humans, Vol. 27, No.4, July 1997), herein referred to as **Wagner**.

14. As to **Claims 1 and 2, Wagner** teaches an apparatus for simulating an electrical sensor/actuator component comprising: a drive module including a model of the sensor/actuator component **(page 481, column 2, lines 5-9)**, said drive module generating interface signals in accordance with signals of said sensor/actuator component **(page 487, section III, lines 14-17)**, said drive module further including at least one signal interface **(Figure 5, "Hardware Interfaces")**, wherein at least one signal interface generates, for each said interface connection pin, one of said interface signals corresponding to the electrical signals of the said sensor/actuator component **(page 488, column 1, section A, paragraph 1, lines 7-10)**, wherein each of said at least one signal interface includes a control/regulation circuit **(page 488, column 1, section A, second paragraph, lines 3-7)**, wherein said apparatus includes modular construction in order to provide a separate signal interface for each interface component **(Figure 5,**

"Hardware Interfaces" show a modular design including Powertrain Simulation, Antilock Brake and Motor Load which are all separate signal interfaces).

15. As to **Claims 3 and 13**, **Wagner** teaches the drive model further includes means for calculating mathematical modules for driving at least one signal interface and wherein said module generates real-time signals in order to obtain said interface signals in accordance with the simulated sensor/actuator components at the interface connection pins **(Page 487, section III, lines 9-17 and Figure 5, "Simulation Computer")**.

16. As to **Claims 4 and 14**, it is concluded that since components in a design must be mounted on a printed circuit board, the controller as shown in **Wagner Figure 5**, being an actual hardware component, must be mounted on a printed circuit board. Further, it is concluded that a design on a printed circuit board will include interface connections to any system that is needed to realize the design, allowing connection to the interface pins in the component that will be receiving or transmitting signals to the system.

17. As to **Claims 5,6,15, and 16**, **Wagner** teaches signal interface has an output stage that can function to output power or receive power. **Figure 5** shows the signal interfaces providing two-way communication between the simulated models and the controller. Further, **page 488, column 1, section A, lines 3-10** state that the PSI and ABI signal interfaces perform signal conditioning which is applied to outputs from the controller or from the RTS, signifying that this interface functions to output power (from the RTS) or receive power (from the controller).

18. As to **Claims 7 and 17**, **Wagner** teaches said drive model comprising a computer for providing an equivalent circuit of the sensor/actuator component as said model **(page 481, column 2, lines 3-9)**.

19. As to **Claims 8 and 18**, **Wagner** teaches said model is adapted to signals required at an interface connection pin by utilizing specific parameters **(page 488, column 2, second paragraph, lines 11-14)** as an example, wherein the commanded motor current is measured by the interface unit and supplied as input to the motor driver model executing in the simulation computer.

20. As to **Claims 9 and 19**, **Wagner** teaches a fault simulation module for generating one of a line interruption and a short circuit **(Figure 5, "Failure Module" and page 488, column 2, last paragraph)**.

21. As to **Claims 10 and 20**, **Wagner** teaches each signal interface has a regulating circuit for adjusting one of voltage and current to a value specified by said model **(page 488, column 1, section A, paragraph 1, section A, paragraph 2, lines 3-14)**.

22. As to **Claim 11 and 12, Wagner** teaches the regulating circuit includes a feedback arrangement to the drive module in order to provide actual values of regulated variables to said model **(page 488, lines 11-20)**.

Conclusion

23. The prior art made of record and not relied upon is considered pertinent to applicant's disclosure.

24. Raman et al (Raman et al, "Design and Implementation of HIL Simulators for Powertrain Control System Software Development". Proceedings of the American Control Conference, June 1999, pages 709-713) teach a hardware-in-the-loop simulation system including actuator and sensor models.

25. Any inquiry concerning this communication or earlier communications from the examiner should be directed to Mary C. Hogan whose telephone number is 703-305-7838. The examiner can normally be reached on 7:30AM-5PM Monday-Friday. If attempts to reach the examiner by telephone are unsuccessful, the examiner's supervisor, Kevin Teska can be reached on 703-305-9704. The fax phone number for the organization where this application or proceeding is assigned is 703-872-9306. Information regarding the status of an application may be obtained from the Patent Application Information Retrieval (PAIR) system. Status information for published applications may be obtained from either Private PAIR or Public PAIR. Status information for unpublished applications is available through Private PAIR only. For more information about the PAIR system, see http://pair-direct.uspto.gov. Should you have questions on access to the Private PAIR system, contact the Electronic Business Center (EBC) at 866-217-9197 (toll-free).

Mary C Hogan
Examiner
Art Unit 2123

KEVIN J. TESKA
SUPERVISORY
PATENT EXAMINER

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Form PTO-1449 U.S. Department of Commerce Patent & Trademark Office	Atty. Docket No. 225/49512	Serial No. NOT YET ASSIGNED
INFORMATION DISCLOSURE STATEMENT *(Use several sheets if necessary)*	Applicants JOERG DRESCHER ET AL.	
	Filing Date January 16, 2001	Group Art Unit:

U.S. PTO 09/759603 JC929 01/16/01

U.S. PATENT DOCUMENTS

Examiner Initial		Document Number	Date	Name	Class	Sub-Class	Filing Date (if appropriate)
MCH	AA	4,325,251	4-20-82	Kanegae	73	119 A	
	AB						
	AC						
	AD						
	AE						

FOREIGN PATENT DOCUMENTS

		Document	Date	Country	Class	Sub-class	Translation Yes | No
MCH	AF	DE 30 24 266	1-15-81	Germany			abstract
MCH	AG	DE 42 12 890	10-21-93	Germany	abs		abstract
	AH						
	AI						
	AJ						
	AK						
	AL						

OTHER DOCUMENTS (Including Author, Title, Date, Pertinent Pages, Etc.)

	AM	
	AN	
	AO	

EXAMINER Mary C. Hogan	DATE CONSIDERED 7/12/04

EXAMINER: Initial if citation considered, whether or not citation is in conformance with MPEP 609; Draw line through citation if not in conformance and not considered. Include copy of this form with next communication.

Notice of References Cited	Application/Control No. 09/759,603	Applicant(s)/Patent Under Reexamination DRESCHER ET AL.	
	Examiner Mary C Hogan	Art Unit 2123	Page 1 of 1

U.S. PATENT DOCUMENTS

*		Document Number Country Code-Number-Kind Code	Date MM-YYYY	Name	Classification
	A	US-			
	B	US-			
	C	US-			
	D	US-			
	E	US-			
	F	US-			
	G	US-			
	H	US-			
	I	US-			
	J	US-			
	K	US-			
	L	US-			
	M	US-			

FOREIGN PATENT DOCUMENTS

*		Document Number Country Code-Number-Kind Code	Date MM-YYYY	Country	Name	Classification
	N					
	O					
	P					
	Q					
	R					
	S					
	T					

NON-PATENT DOCUMENTS

*		Include as applicable: Author, Title Date, Publisher, Edition or Volume, Pertinent Pages)
	U	Wagner et al, "A Strategy to Verify Chassis Controller Software-Dynamics, Hardware and Automation", IEEE Transactions on Systems, Man, and Cybernetics-Part A: Systems and Humans, Vol. 27, No.4, July 1997
	V	Raman et al, "Design and Implementation of HIL Simulators for Powertrain Control System Software Development". Proceedings of the American Control Conference, June 1999, pages 709-713
	W	
	X	

*A copy of this reference is not being furnished with this Office action. (See MPEP § 707.05(a).)
Dates in MM-YYYY format are publication dates. Classifications may be US or foreign.

A Strategy to Verify Chassis Controller Software—Dynamics, Hardware, and Automation

John R. Wagner and John F. Keane, *Member, IEEE*

Abstract— **A real-time hardware-in-the-loop tool set is presented to test automotive chassis controllers. The use of high-speed computers, specialized hardware interfaces, and instrumentation, as well as simulation models and automation software, provide a realistic and repeatable laboratory environment to supplement in-vehicle testing. In this paper, the dynamics for a variety of chassis models are presented to support the verification of integrated controller hardware and software. To implement these mathematical descriptions the computer hardware, laboratory equipment, and simulation software are discussed. The automated testing features of the simulator permit the creation of script files and test suites for regression testing and reuse on similar programs. A number of issues such as simulator requirements, hardware interfaces, and the need for metrics are explored in order to facilitate the development and justification of a simulation capability.**

NOMENCLATURE

a	Distance from GG to front axle, (m).
a_{off}	Vertical pressure center long. offset, (m).
A_d	Cross sectional area, (m^2).
AT	Wheel aligning torque, (N*m).
$\overline{AT}$	Aligning torque, ({N*m}/rad).
b	Distance from CG to rear axle, (m).
c	Half of front wheel track, (m).
C_α	Lateral tire stiffness, (N/rad).
$C_{\alpha_f}, C_{\alpha_r}$	Front, rear total cornering stiffness, (N/rad).
C_d	Aerodynamic drag coefficient.
C_w	Wheel damping coefficient, ({N*m}/{rad/s}).
CG	Center of gravity.
d	Half of rear wheel track, (m).
d_ϕ	Suspension pitch damping, (N/{m*rad/s}).
d_θ	Shock absorber roll damping, (N/{m*rad/s}).
D	Rolling tire resistance, (N).
$\overline{D}$	Rolling resistance, (N).
e	x-distance from king pin to wheel CG, (m).
f	y-distance from king pin to wheel CG, (m).
F_{coul}	Suspension Coulomb damping force, (N).
F_d	Aerodynamic drag force, (N).
F_{damp}	Suspension viscous damping force, (N).
F_s	Suspension force, (N).
F_{spring}	Suspension spring force, (N).
F_{xw}	Longitudinal tire force in wheel plane, (N).
F_x	Tire force along forward body axis, (N).
F_{yw}	Lateral tire force in wheel plane, (N).
F_y	Tire force along lateral body axis, (N).
F_z	Normal tire load, (N).
ΔF_z	Vertical load transfer, (N).
ΣF_x	Sum of longitudinal forces, (N).
ΣF_y	Sum of lateral forces, (N).
g	Acceleration constant, (m/s^2).
h	Center of gravity height, (m).
h'	Distance from wheel center to ground, (m).
h_a	Distance from CG to aerodynamic force, (m).
h_s	Height of sprung mass CG above roll axis, (m).
$i_a, \tilde{i}_a$	Actual and estimated motor current, (amps)
$i_c, \hat{i}_c$	Commanded and measured motor current, (amps).
$i_{c_{\text{serial}}}$	Serial value of commanded motor current.
I_{wy}	Wheel inertia about spin axis, (kg*m^2).
I_x	Sprung mass inertia about roll axis, (kg*m^2).
I_{xz}	Vehicle inertia about x and z axes, (kg*m^2).
I_{yy}	Vehicle inertia about pitch axis, (kg*m^2).
I_{zz}	Vehicle inertia about yaw axis, (kg*m^2).
k_θ	Suspension roll stiffness, ({N*m}/rad).
k_ϕ	Suspension pitch stiffness, (N/{m*rad}).
m	Total vehicle mass, (kg).
m_s	Sprung mass, (kg).
ΣM_x	Sum of moments about roll axis, (N*m).
ΣM_y	Sum of moments about pitch axis, (N*m).
ΣM_z	Sum of moments about yaw axis, (N*m).
R	Undeflected tire radius, (m).
R_e	Effective radius, (m).
S_x	Longitudinal wheel slip.
t	Time, (s).
t_s	Distance between vehicle longitudinal center line and shock absorber, (m).
T_b	Wheel brake torque, (N*m).
T_d	Wheel driveline torque, (N*m).
u, u_i	Longitudinal vehicle, wheel center speed, (m/s).
u_w	Wheel center speed in wheel plane, (m/s).
v, v_i	Lateral vehicle, wheel center speeds, (m/s).
$\vec{V}$	Velocity, (m/s).
w_x	Vehicle roll angular speed, (rad/s).
w_y	Vehicle pitch angular speed, (rad/s).
w_z	Vehicle yaw angular speed, (rad/s).
x	Body fixed longitudinal axis.

Manuscript received May 28, 1995; revised April 14, 1996 and June 14, 1996.

The authors are with the Systems Technology Department, Delco Electronics Corporation, Kokomo, IN 46904-9005 USA (e-mail: jrwagner@eng.delcoelect.com).

Publisher Item Identifier S 1083-4427(97)03475-9.

X	Global vehicle longitudinal position, (m).
y	Body fixed lateral axis.
Y	Global vehicle lateral position, (m).
$\bar{Y}$	Vehicle side force, (N).
z	Body fixed vertical axis; height of roll axis above ground at axle, (m).
Z	Global vehicle vertical position, (m).
α	Tire side slip angle, (rad).
β	Vehicle sideslip angle, (rad).
δ	Steer angle of wheel, (rad).
γ	Wheel camber angle, (rad).
μ	Friction coefficient.
ω	Angular velocity of the wheel, (rad/s).
ρ	Mass density of air, (kg/m^3).
ϕ	Vehicle pitch angle, (rad).
θ	Vehicle roll angle, (rad).
ψ	Vehicle yaw angle, (rad).
ϵ	Roll steer $\{\partial\delta/\partial\theta\}$, (rad/rad).
$\{\partial AT/\partial\alpha\}$	Change in aligning torque versus slip, ({N*m}/rad).
$\{\partial D/\partial F_z\}$	Change in rolling resistance with load, (N/N).
$\{\partial L/\partial w_x\}$	Roll damping produced by the shock absorbers, {N*m*s}/rad).
$\{\partial\bar{Y}/\partial\gamma\}$	Camber thrust per unit camber angle, (N/rad).
$\{\partial\gamma/\partial\theta\}$	Rate of wheel camber angle change with respect to body roll angle, (rad/rad).
Subscripts:	
b	Brake.
$fail$	Failure.
f, r	Front, rear axles.
i, j	ith, jth wheel and axle location.
1, 2	Right, left front wheels.
3, 4	Right, left rear wheels.

I. Introduction

The application of on-board electronic controllers to monitor and regulate automotive systems offers the consumer improved vehicle performance. Powertrain controllers monitor all major engine and transmission functions to realize significant reductions in tailpipe emissions with minimum adverse effects on fuel economy and vehicle driveability. Body and chassis control systems (e.g., antilock brakes, real-time suspension damping) provide increased safety and ride comfort to the vehicle occupants through improvements in directional stability and steerability [1]. Traditionally, the development process for automotive systems has involved extensive in-vehicle testing and evaluation. However, the competitive demands of the marketplace are requiring automotive companies to reduce cycle time and development costs. The application of hardware-in-the-loop (HIL) technology to the controller design process can reduce expensive field tests, improve product quality, facilitate examination of subsystem interactions, and resolve critical safety issues prior to in-vehicle testing [2]. In particular, the system level verification and validation of integrated chassis controller hardware/software to the customer's requirements can be automated in a laboratory setting with HIL tools.

A HIL simulator permits an automotive controller to be operated in an environment electronically equivalent to the actual vehicle (refer to Fig. 1). The simulator contains electronic circuits which provide electrical loads representative of those found in an actual vehicle. A high-speed computer is interfaced to the controller through the actuator and sensor emulation hardware. The computer executes dynamic system models to calculate the vehicle's response and generate sensor signals for the driver inputs and controller commanded actuator signals. Thus, a dynamic coupling is established between the controller and the simulated vehicle. In this paper, the hardware and software elements of an automotive chassis simulator are presented. Section II provides an overview of various vehicle subsystem models. The simulation computer and laboratory hardware are presented in Section III. In Section IV, the software utilities necessary to automate the testing process, as well as several methods to verify controllers, are discussed. Section V presents experimental and simulation results to provide insight into the application of the tool set. A number of key simulation issues are discussed in Section VI that should be addressed early in the development process.

II. Simulation of Chassis Dynamics

The creation of a model-based automotive simulation requires the availability of empirical and analytical mathematical descriptions of the system components. As shown in Fig. 2, the chassis dynamics are generally composed of the vehicle, wheel, brakes, steering, suspension, tire/road interface, driver, environment, and in some instances, powertrain dynamics. The vectors X_i have been introduced to permit the primary output elements from each subsystem to be denoted. For instance, the brake system block has the output vector X_2 which includes the brake pressures and torques for each brake channel. The inputs to this subsystem include the variables from the engine, transmission, and engine control module (X_1), the ABS/TCS controller (X_9), and the driver (X_{10}) blocks. Models for each of the vehicle's subsystems should be available with varying degrees of sophistication. The complexity of a component model may then be selected in order to create a simulation tailored for the application that is not overly excessive. This is an important issue in real-time simulations where a tradeoff often exists between model fidelity and execution speed requirements. In the paper by Allen and Rosenthal [3], vehicle dynamics model requirements are summarized for various types of simulations. The chassis models presented in this paper are sufficient for software verification.

The environment block contains software modules which allow the road surface properties and elevation to be varied as functions of the vehicle's location. For instance, a composite road surface may be characterized by specifying the friction coefficients in a position indexed lookup table [4]. The vehicle's global position is then used to determine the nominal coefficient of friction for each wheel. In the driver block, vehicle maneuvering information is described through traditional driver commands. These commands may be generated by the user during run-time by manipulating the

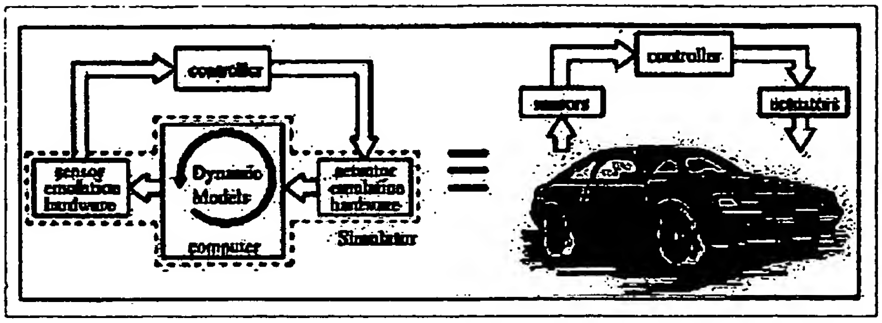

Fig. 1. Conceptual goal for hardware-in-the-loop testing.

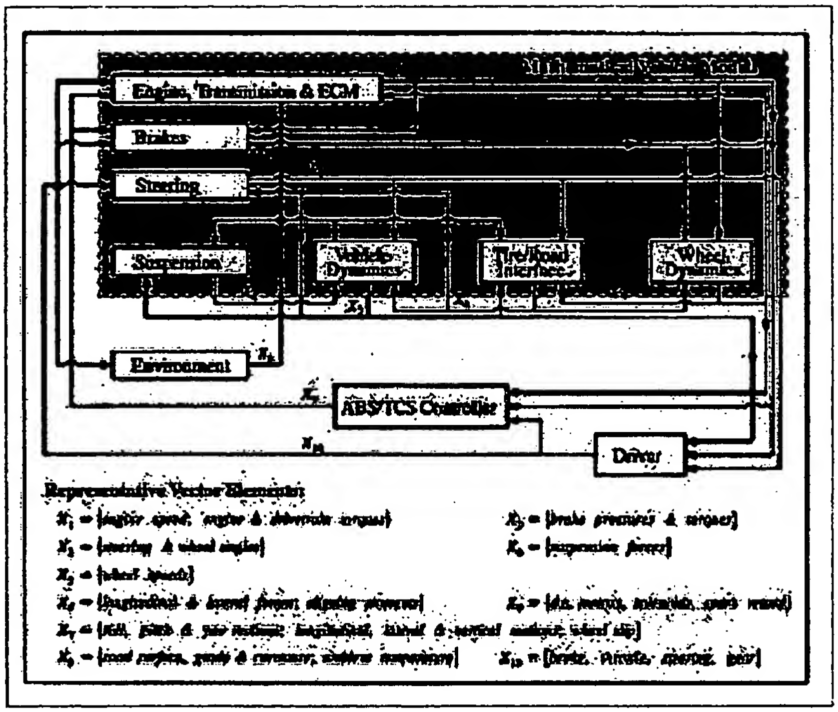

Fig. 2. Schematic for simulating chassis dynamics.

hardware interface, or stored *a priori* through the use of script files to automate the system's operation.

A. Vehicle and Suspension Dynamics

The motions of a vehicle may be categorized in terms of performance and ride, as well as handling and stability. The performance and ride characteristics focus on the longitudinal and heave motions of the platform, respectively. The stability and handling characteristics generally refer to the vehicle's lateral/directional response due to steering maneuvers. A variety of low, medium, and high-order models are available to describe the automobile's translational and rotational dynamics.

1) Low-Order Models: A one degree-of-freedom (DOF) vehicle model is sufficient in cases where a lumped mass approach is acceptable to generate the platform's speed. The equation of motion in the longitudinal direction is

$$m\dot{u} = \Sigma F_x \tag{1}$$

This description has been successfully used in powertrain simulations which require only an approximate speed to emulate the vehicle's speed sensor for engine algorithm testing. However, limitations in the vehicle dynamics preclude the use of this model in chassis controller studies.

A two DOF model is presented for lateral stability investigations. In this analysis, the vehicle's front and rear wheels are collapsed into a single front (steerable) and rear wheel with negligible inertia. Also, the roll and weight transfer effects are neglected. This "bicycle" model permits the lateral/directional response of the platform to be examined for small angle steering maneuvers at constant longitudinal speed [5]. Body fixed (xyz) and global (XYZ) coordinate systems are used to describe the dynamics (refer to Fig. 3). The equations of

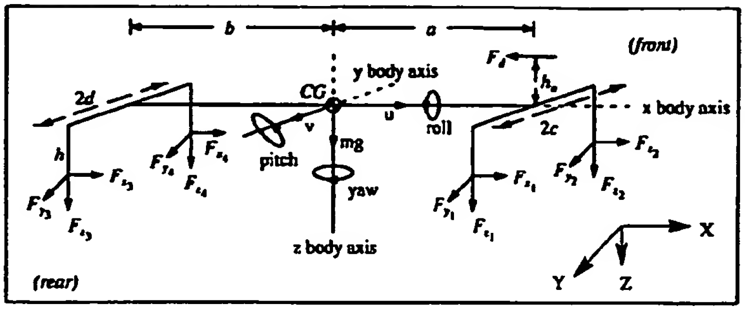

Fig. 3. Axis system for simplified vehicle models.

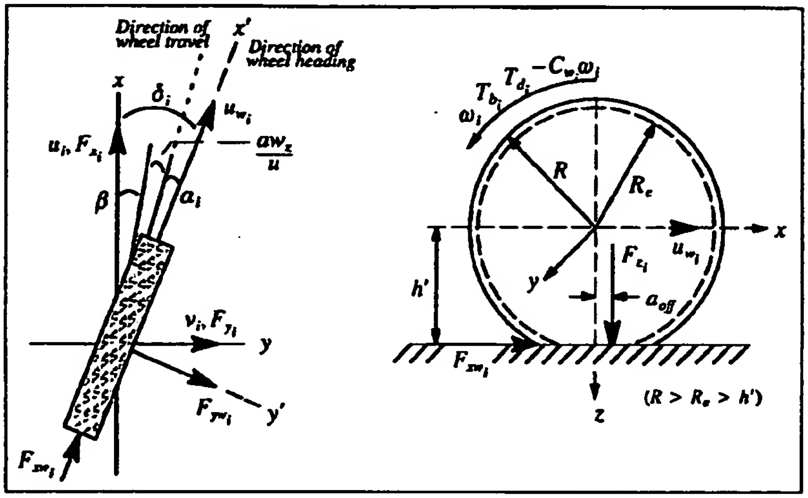

Fig. 4. Directional geometry and rotational wheel dynamics.

motion for forces along the y-axis and moments about the z-axis are

$$m(\dot{v} + uw_z) = \Sigma F_y \tag{2}$$

$$I_{zz}\dot{w}_z = \Sigma M_z \tag{3}$$

As shown in Fig. 4, the wheel is rolling at a slip angle α which represents the angle formed between the direction of wheel travel and wheel heading. The front and rear slip angles become

$$\alpha_f = \{v + aw_z\}/u - \delta_f \quad \alpha_r = \{v - bw_z\}/u. \tag{4}$$

In some cases, a front and rear roll steer effect ($\epsilon\theta$) may also be included in the slip angle expressions. From this figure, $\beta = \{v/u\}$ represents the vehicle sideslip angle. To further simplify the analysis, it is assumed that the slip angles are small ($\sin\alpha = \alpha$) and that the lateral tire forces are linear functions of the slip angles. If the lateral accelerations are greater than approximately 0.4 g's, then this final assumption may no longer be acceptable. The summation of lateral forces and moments about the yaw axis is

$$\Sigma F_y = C_{\alpha_f}\alpha_f + C_{\alpha_r}\alpha_r \quad \Sigma M_z = aC_{\alpha_f}\alpha_f - bC_{\alpha_r}\alpha_r. \tag{5}$$

In these equations, the cornering stiffness has a negative magnitude since a positive slip angle produces a negative lateral force acting on the tire [6]. However, in some references (e.g., [7]), the cornering stiffness has a positive magnitude resulting from its definition as the negative of $\{\partial F_y/\partial\alpha\}$. Equations (2) and (3) may be numerically integrated to yield the lateral and yaw velocities in the local coordinate system. These body axis velocities may be transformed into velocities in the global reference system by

$$\dot{X} = u\cos\psi - v\sin\psi \quad \dot{Y} = u\sin\psi + v\cos\psi \tag{6}$$

where ψ is numerically integrated from $\dot{\psi} = w_z$. Finally, the vehicle's position in global coordinates may be determined by integrating the expressions in (6).

2) Medium Order Models: A three DOF model is presented to describe the longitudinal, lateral, and yaw motions of an automobile undergoing maneuvers [8]. This model combines vehicle kinematics, tire forces, and wheel dynamics to create a general purpose simulation suitable for preliminary antilock brake system (ABS) and traction control studies. The equations of motion are

$$m(\dot{u} - vw_z) = \Sigma F_x \tag{7}$$

in the longitudinal direction and (2) and (3). From Fig. 3, the external forces acting on the vehicle are

$$\Sigma F_x = \sum_{i=1}^{4} F_{x_i} - F_d \quad \{\text{where } F_d = 0.5 C_d \rho A_d u^2\} \tag{8}$$

$$\Sigma F_y = \sum_{i=1}^{4} F_{y_i}. \tag{9}$$

The summation of moments about the yaw axis are

$$\Sigma M_z = a(F_{y_1} + F_{y_2}) - b(F_{y_3} + F_{y_4}) + c(F_{x_2} - F_{x_1}) + d(F_{x_4} - F_{x_3}). \tag{10}$$

In this expression, the aligning torques have been neglected and should be added if required. Equations (2), (3), and (7) may be numerically integrated to determine the lateral, yaw, and longitudinal velocities in the body axis coordinate system.

The speed of each wheel center in the wheel plane may be calculated as

$$u_{w_i} = u_i \cos\delta_i + v_i \sin\delta_i \tag{11}$$

where the longitudinal and lateral velocities at each corner of the vehicle are given by

$$u_i = u + (-1)^i c w_z \quad v_i = v + a w_z \qquad (i = 1, 2) \tag{12a}$$

$$u_j = u + (-1)^j d w_z \quad v_j = v - b w_z \qquad (j = 3, 4). \tag{12b}$$

Again, the vehicle velocity may be transformed from the local coordinate system into the global reference system using the transformations in (6).

For completeness, a model developed by Segel [9] which analyzes lateral vehicle motion in response to steering inputs will be discussed. The assumptions for this model include a constant forward velocity, small lateral accelerations, and symmetry about the x-axis which allows a single front and rear wheel to be considered. The equations of motion for the sideslip, roll, and yaw in a two mass (sprung and unsprung) system with an inclined roll axis are

$$m(\dot{v} + u w_z) + m_s h_s \dot{w}_x = \Sigma F_y \tag{13}$$

$$I_z \dot{w}_z + m_s h_s(\dot{v} + u w_z) + I_{xz} \dot{w}_z = \Sigma M_z \tag{14}$$

$$I_{xz} \dot{w}_x + I_{xz} \dot{w}_z = \Sigma M_x. \tag{15}$$

The lateral forces acting on the platform are

$$\Sigma F_y = \tilde{Y}_f + \tilde{Y}_r \tag{16}$$

where

$$\tilde{Y}_i = C_{\alpha_i} \alpha_i + \{\partial \tilde{Y}_i / \partial \gamma_i\}\{\partial \gamma_i / \partial \theta\}\theta$$

includes the cornering force and tire camber effects. The chassis characteristic $\{\partial \gamma_i / \partial \theta\}$ is experimentally measured for the vehicle. The torques contributing to the roll moment are

$$\Sigma M_x = (m_s g) h_s \theta + (k_{\theta_f} + k_{\theta_r})\theta + [\{\partial L / \partial w_x\}_f + \{\partial L / \partial w_x\}_r] w_x. \tag{17}$$

In this expression, the roll damping produced by the shock absorbers may be approximated as $\{\partial L / \partial w_x\}_i = 2 d_{\theta_i} t_{s_i}^2$. The summation of torques for the yaw moment are

$$\Sigma M_z = (a\tilde{Y}_f - b\tilde{Y}_r) + (\overline{AT}_f + \overline{AT}_r) + 2(c\overline{D}_f + d\overline{D}_r) \tag{18}$$

where

$$\overline{AT}_i = \{\partial AT_i / \partial \alpha_i\}\alpha_i \quad \text{and} \quad \overline{D}_i = \{\partial D_i / \partial F_{z_i}\}\Delta F_{z_i}.$$

The load transfer ΔF_{z_i} may be calculated as $\zeta_i(\tilde{Y}_i z_i + k_{\theta_i}\theta + \{\partial L / \partial w_x\}_i w_x)$ with $\zeta_i = 1/\{2c\}$ or $1/\{2d\}$ depending on whether the front or rear axle is under consideration. In the expressions for $\tilde{Y}_i, \overline{AT}_i$, and $\overline{D}_i$, the terms $\{\partial \tilde{Y}_i / \partial \gamma_i\}, \{\partial AT_i / \partial \alpha_i\}$, and $\{\partial D_i / \partial F_{z_i}\}$ are empirically defined tire characteristics (Section II-B). Equations (16)–(18) may next be expressed as functions of $(\beta, w_z, \theta, \delta_f, w_x)$. The resulting differential equations are traditionally solved with classical methods to study the influence of various design parameters on the vehicle's stability. The reader is referred to the reference by Mola [10] for further information.

A four DOF model is presented to describe the longitudinal, lateral, yaw and pitch motions of an automobile. This model provides a general purpose description of the vehicle dynamics which can serve both powertrain and chassis applications well. The equations of motion are

$$I_{yy} \dot{w}_y = \Sigma M_y \tag{19}$$

and (2), (3), and (7). The summation of forces and moments (refer to Fig. 3) are (9) and

$$\Sigma F_x = -mg\sin\phi + \sum_{i=1}^{4} F_{x_i} - F_d \tag{20}$$

$$\Sigma M_z = a(F_{y_1} + F_{y_2}) - b(F_{y_3} + F_{y_4}) + c(F_{x_2} - F_{x_1}) + d(F_{x_4} - F_{x_3}) - e(F_{y_1} + F_{y_2}) + f(F_{x_1} - F_{x_2}) + \sum_{i=1}^{4} AT_i \tag{21}$$

$$\Sigma M_y = -a(F_{s_1} + F_{s_2}) + b(F_{s_3} + F_{s_4}) + \sum_{i=1}^{4} hF_{x_i} + h_a F_d. \tag{22}$$

The transformations to calculate the yaw, pitch, and approximate roll angular velocities, based on w_y and w_z, are

$$\dot{\psi} = w_z \quad \dot{\phi} = w_y \quad \dot{\theta} = w_z \phi. \tag{23}$$

These expressions may be numerically integrated to calculate the yaw and pitch, as well as approximate roll, angles. In a similar manner, the transformations to compute the global velocities

$$\dot{X} = u\cos\phi\cos\psi - v\sin\psi \quad \dot{Y} = v\cos\psi + u\sin\psi\cos\phi$$
$$\dot{Z} = -u\sin\phi \tag{24}$$

may be integrated to determine the global positions.

Depending on the intended application of the simulation, the model for the suspension forces may be simplistic or quite

complex. Generally, a suspension model will include spring forces as well as viscous and Coulomb damping forces

$$F_{s_i} = F_{\mathrm{spring}_i} + F_{\mathrm{damp}_i} + F_{\mathrm{coul}_i}. \quad (25)$$

The suspension springs (coil, leaf, or torsional bars) support the weight of the car and characterize the ride behavior of the platform. The spring force is a nonlinear function of the suspension's deflection. Frequently, a series of linear regions are considered over the range of vertical travel to approximate the nonlinear behavior. For the four DOF vehicle model, the front and rear spring forces can be represented as $(a\phi)k_{\phi_f}$ and $-(b\phi)k_{\phi_r}$ where k_ϕ may be interpolated from a lookup table or further approximated by a constant magnitude. The term F_{damp} represents the hydraulic shock absorbers (or struts) which dampen the vehicle's motion. In many analyzes, these viscous damping elements are modeled as ideal fluid dampers whose force is proportional to the suspension's rate of deflection. Again, the nonlinear damping force versus velocity curve may be approximated by straight line segments. The front and rear damping forces can be represented as $(a w_y)d_{\phi_f}$ and $-(b w_y)d_{\phi_r}$ where d_ϕ may be determined in a similar manner to k_ϕ. Finally, the coulomb damping force is also a function of the suspension's deflection rate. This friction force is quick acting and has a saturation feature normally described by limit functions. In some applications the rubber bushings, which act as vibration isolators to minimize transmission of higher frequency oscillations, and/or anti-sway bars may also need to be considered in the suspension model.

3) High-Order Models: If a more sophisticated vehicle description is needed to study dynamic interactions, then a higher order model using sprung and unsprung masses is recommended. Two vehicle stability and control simulations are available to study handling and braking capabilities for a range of maneuvers. The simulation by Garrott and Scott [11] considers a three mass system—sprung, front unsprung and rear unsprung. The sprung mass has six DOF (three translations and three rotations). The unsprung masses each have two DOF if the wheel spins and steering dynamics are not counted. The front unsprung mass has two translations relative to the sprung mass to describe the wheel hop. For the rear unsprung mass, the independent suspension model includes two suspension deflections while the solid axle description considers one suspension deflection and one axle roll. Overall, this vehicle model provides a comprehensive description of the system dynamics. The second model has been developed by Allen *et al.* [12] to analyze vehicle lateral/directional control and stability. In this model, a three mass system is also considered. The sprung mass has four DOF (longitudinal, lateral, yaw, and roll) while each unsprung mass has two DOF, again not counting the wheel spins and steering dynamics. For the front and rear unsprung masses, the roll and vertical motion of the respective axles are considered. In addition to modeling the vehicle dynamics, these two simulations provide descriptions for the wheels, suspension, steering, and tire/road interface.

An important issue in the development of real-time simulations is the tradeoff between model sophistication and execution speed. Ideally, all the system dynamics may be adequately addressed when developing a model. However, real-time requirements may challenge the engineer to exclude some dynamics in order to achieve a mathematical description which may be computed in real time. Associated with this issue is the correlation, or level of accuracy, of the simulation to the physical system for a specified operating range. Heydinger *et al.* [13] has proposed a statistical based validation methodology which requires multiple experimental and simulation runs at each test condition to gather data for both frequency and time domain analysis. A series of qualitative (e.g., overlaying plots) and quantitative (e.g., steady state gain, peak frequency) strategies are presented to compare the test measurements and simulation predictions.

B. Tire/Road Interface

The shear forces and aligning torques generated at the tire/road interface must be computed to simulate the wheel and chassis dynamics. To quantify the impact of applied braking or driving torques on a wheel, the tire's side slip angle and wheel slip are calculated. As shown in Fig. 4, a local coordinate system (x', y', z') has been attached to the wheel with its origin at the center of tire contact. Although the side slip angle was introduced in (4), the expression is now stated as

$$\alpha_i = \tan^{-1}(v_i/u_i) - \delta_i. \quad (26)$$

The longitudinal wheel slip is defined in two manners depending on whether the wheel is accelerating or decelerating

$$\begin{aligned} \text{drive slip: } s_{x_i} &= (u_{w_i} - R_{e_i}\omega_i)/R_{e_i}\omega_i \\ \text{brake slip: } s_{x_i} &= (u_{w_i} - R_{e_i}\omega_i)/u_{w_i}. \end{aligned} \quad (27)$$

To calculate the shear forces and aligning torques, the normal tire load must also be available. In the model proposed by Dugoff *et al.* [8], the static loading and quasistatic load transfer due to pitching, as well as the quasistatic approximation of the dynamic load transfer due to the vehicle's roll angle, are considered

$$\begin{aligned} F_{z_j} = 0.5\Bigg\{&\left(\frac{1}{a+b}\right)\left(-bmg + h\sum_{i=1}^{4} f_{x_i} + h_a F_d\right) \\ &+ (-1)^{(j+1)}(k_{\theta_f}/\{k_{\theta_f} + k_{\theta_r}\})(hF_y/c)\Bigg\} \quad (j = 1, 2) \end{aligned} \quad (28a)$$

$$\begin{aligned} F_{z_j} = 0.5\Bigg\{&\left(\frac{1}{a+b}\right)\left(-amg - h\sum_{i=1}^{4} f_{x_i} - h_a F_d\right) \\ &+ (-1)^{(j+1)}(k_{\theta_r}/\{k_{\theta_f} + k_{\theta_r}\})(hF_y/d)\Bigg\} \quad (j = 3, 4). \end{aligned} \quad (28b)$$

Generally, the traction forces for a variety of road surfaces and operating conditions may be generated using two strategies: extrapolation of empirical data, and analytic models. In the first method, experimentally gathered tire data is loaded into look up tables and an extrapolation scheme [14] is implemented to describe road conditions that are not explicitly contained in the test data. Frequently, experimental tire data

is limited to a few road surfaces (e.g., dry asphalt, asphalt with thin water film) and operating conditions (e.g., side slip angle, normal load). From this experimental data, the longitudinal tire force versus wheel slip provides a measure of the braking/driving force coefficient $\{F_x/F_z\}$. The lateral tire force versus slip angle graph provides the cornering stiffness $C_\alpha = \{\partial F_y/\partial\alpha\}_{\alpha=0}$. The aligning torque versus slip angle and camber thrust versus camber angle graphs can yield $\{\partial AT/\partial\alpha\}$ and $\{\partial \bar{Y}/\partial\gamma\}$, respectively. Finally, the tire's rolling resistance versus vertical load at a specified forward velocity provides the quantity $\{\partial D/\partial F_z\}$.

The second strategy uses mathematical models to estimate the mechanical performance of pneumatic tires from basic design and operating variables. These models range from simple linear descriptions useful in deriving and analyzing control systems to nonlinear representations [15]–[17] with tire lag [18]. The tire forces and aligning torque are calculated based on the longitudinal wheel slip, wheel speed, side slip angle, normal load, and other variables (e.g., camber angle). These forces in the wheel plane may be transformed into longitudinal and lateral forces in the vehicle coordinate system by

$$F_{x_i} = F_{xw_i}\cos\delta_i - F_{yw_i}\sin\delta_i \; F_{y_i} = F_{xw_i}\sin\delta_i + F_{yw_i}\cos\delta_i \tag{29}$$

C. Wheel Rotational Dynamics

The forces and torques acting on the ith wheel from the transmission, brakes, road surface, vehicle, and wheel bearings are shown in Fig. 4. The summation of moments about the spin axis are

$$I_{wy}\dot{\omega}_i = T_{b_i} + T_{d_i} + F_{xw_i}h' - F_{z_i}a_{\text{off}} - C_{w_i}\omega_i. \tag{30}$$

Several approaches may be used to calculate the wheel speeds, including the direct integration of the rotational dynamics and a closed form solution based on the linearized μ-slip curve. In the first method, (30) is numerically integrated. However, these dynamics are very fast compared to the overall vehicle dynamics which can result in stiff differential equations (i.e., system eigenvalues vary widely in magnitude). This phenomenon arises from the large mass and moments of inertia for the vehicle in comparison to the small rotational inertias of the wheels and large torques experienced from the braking, driveline, and ground forces. If the high-frequency wheel dynamics are not properly handled, then numerical instabilities may arise. A number of solutions are available to avoid numerical integration stability problems. First, reduce the integration time step as allowed by the execution speed constraints. Second, select a numerical integration method with accuracy and stability characteristics suitable for the application. Improved accuracy may be realized by using smaller time steps or by selecting a higher order integration algorithm. However, higher order integration methods may have smaller stability regions which will require smaller integration time steps. Third, consider restricting the simulation to avoid unstable domains of operation. For instance, an ABS simulation might terminate when the vehicle velocity falls below some specified threshold (e.g., $\vec{V} < 1$ MPH). Although this solution may be acceptable for ABS simulations since control algorithms cease operation in this region, it is probably not optimal in traction control studies where low vehicle velocities are of interest.

The second strategy to simulate the wheel spin dynamics is based on the work by Bernard [19]. The nonlinear tire traction torque is linearized about the operating point μ_0 by considering a Taylor series expansion of the continuously differentiable μ-slip curve with higher order terms neglected (i.e., $\mu = \mu_0 + \{\partial\mu/\partial s_x\}\{s_x - s_{x_0}\}$). This permits a closed form solution of the first order wheel slip equation to be obtained, thus eliminating the need for numerical integration. The underlying principle of the state transition approach may be used in other simulation applications where the differential equations do not readily lend themselves to numerical integration.

D. Brakes and Steering Dynamics

A base brake model should include descriptions for the pedal linkage, vacuum booster, master cylinder, brake lines, and brake discs or drums [20]. The pedal linkage transmits the driver's applied force to the vacuum booster which amplifies this force using vacuum from the engine's manifold. The master cylinder, attached to the vacuum booster, transforms the amplified force into hydraulic pressure by displacing brake fluid through the front and rear brake lines. Proportioning values distribute the pressure properly between the front and rear axles. The front and rear brakes convert the pressure into a friction force to decelerate the wheel. Although the brake system is nonlinear with dead zones, approximate models (e.g., pure time delay, first order linear dynamics) are frequently used to describe the system's response. However, nonlinear models of the vacuum booster, master cylinder, engine manifold, and proportioning values have been developed (e.g., [21] and [22]) which offer improved accuracy.

The steering module maps the steering wheel inputs into front wheel displacements. Manual steering systems contain a steering wheel and column, a gearbox and pitman arm or a rack and pinion assembly, linkages, steering knuckles and wheel spindles [23]. Power steering systems add a hydraulic pump and power steering gear assembly. In the model derived by Segel [24], a distributed mass steering system is reduced to a lumped mass description with compliance, Coulomb friction, and viscous damping. The inputs are the driver applied steering torque and kingpin torque due to the tire/road interface, while the output is the front wheel displacement. The model proposed by Garrott and Scott [11] calculates the front wheel steering angles and steering connecting rod displacement as functions of the steering wheel angle, moments on the wheels about the kingpins, linkage geometry and stiffness, and gearbox ratio. In some instances, the steering system dynamics may be avoided by assuming an infinitely stiff steering mechanism and by directly providing the front wheel displacements.

E. Engine and Transmission Dynamics

A variety of models have been derived to describe the behavior of spark ignition (SI) and diesel engines for simulation and control purposes. A comprehensive survey has

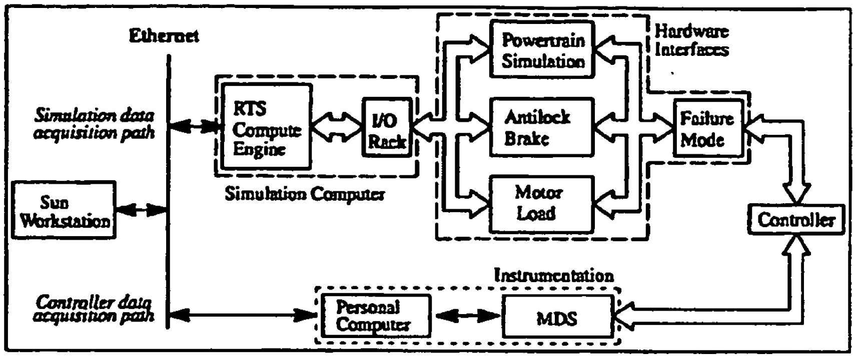

Fig. 5. Hardware-in-the-loop simulator configuration.

been conducted by Powell [25] on internal combustion engine models for control system design. The engine descriptions may be broadly divided into input-output and physical-based models. Multi-input multi-output models are generated by applying system identification techniques to the experimental data (e.g., [26]). The resulting transfer functions are dependent on the specific system configuration, and require engine data to be available over the full operating spectrum. The physical-based models consider fundamental laws governing the flows, thermal transients, and accelerating inertias to describe the behavior of the system components. For real-time HIL testing, the lumped parameter mean value engine models (e.g., [27]–[33]) may be selected as the basis for engine simulations due to the satisfactory accuracy and limited complexity. For diesel engine models, the reader is referred to the work by Benson [34], Watson [35], and Kao and Moskwa [36]. A number of subsystems are generally considered in a turbocharged diesel engine description including the compressor, intercooler, intake manifold, engine and crankshaft assembly, exhaust manifold, turbine, and turbocharger rotor.

Analytical and empirical models in the simulation library describe the fuel injectors, throttle body, intake manifold, combustion process, and rotational dynamics for SI engines [37]. The fuel injector model converts the controller commanded solenoid fuel pulses into a mass of sprayed fuel. The throttle body model computes the mass air flow rate into the intake manifold based on the throttle valve angle, idle air control actuator position, and pressure ratio across the throttle. The intake manifold dynamics distribute and delay the flow of gases from the throttle body and EGR valve into the engine cylinders with attention to fuel transport characteristics, if appropriate. The combustion model generates the indicated torque based on the mass of air, air/fuel ratio, spark timing, and exhaust gas in each cylinder. Finally, the crankshaft torques (e.g., indicated and load) are summed, integrated, and divided by the crankshaft inertia to yield the engine speed.

An automatic transmission transfers and regulates the engine's power to the drive wheels based on the vehicle's traction requirements. A number of models and analysis methods have been proposed to describe the behavior of vehicle transmissions. The interested reader is referred to the references by Benford and Leising [38], Kotwicki [39], and Cho and Hedrick [40]. The transmission modules in the simulation library include the torque converter, transmission gearbox, and differential [37]. The torque converter provides a fluid coupling between the engine and the drivetrain to dampen out disturbances, prevent engine stalling, and provide torque multiplication during vehicle acceleration. To describe these dynamics, the empirical based torque converter models generate the pump and turbine torques based on their respective speeds. Included in this subsystem are the torque converter clutch models which describe the mechanical linkage of the pump and turbine. The automatic transmission gearbox models describe the motions of the planetary gears, clutches, and bands which together provide different torque multiplication ratios based on the engine load conditions. The differential models contain the kinematics of the gears which provide additional torque multiplication, transmit the output torque to each axle, and allow different axle rotation speeds.

III. Simulation Computer and Laboratory Hardware

The real-time HIL simulation facility has been designed to test and analyze automotive controllers. As shown in Fig. 5, the facility consists of a simulation computer, various hardware interfaces, and controller instrumentation. The simulation computer is an Applied Dynamics Real Time Station (RTS) with an attached System 100 input/output (I/O) rack. The computer hardware is based on the open architecture of the VMEbus with distributed processors to execute the simulation models and handle network communications [41]. The RTS contains multiple Motorola 88110 based compute engines to solve the analytical and empirical mathematical descriptions of the system components. In the current configuration, the I/O rack contains analog-to-digital converters, digital-to-analog converters, and digital input/output lines. These intelligent I/O modules contain Motorola 68040 support processors for parallel computing of interface operations such as signal conditioning and linearization. The availability of commercial I/O modules to emulate automotive sensors should minimize the need for specialized hardware interfaces. A local 300 MB disk can support high-speed data recording and playback in real time during and after a simulation.

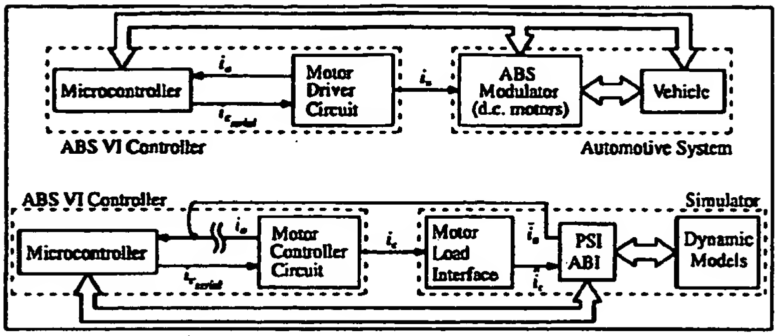

Fig. 6. Architecture for actual and simulated dc motor electrical loads.

Users can access the RTS, a server attached to the local area network, from their workstations connected to the ethernet. In our facility, Sparcstations 20 (model 50) are used to control and monitor the simulation, as well as provide an integrated environment for algorithm development and data analysis. The RTS compute engines can be programmed in C, Fortran, or Adsim [42]. A rapid prototyping capability is available to move quickly from block diagrams and software simulations (using Integrated Systems' MATRIXx product family) to HIL applications on the RTS. The high-level language Cosim is used to schedule, synchronize, and control communications for the parallel processors. Interactive run time software provides an environment to acquire simulation data, and to monitor and control the simulation from the user's workstation.

A. Hardware Interfaces

The hardware interfaces are designed to create an electronic environment equivalent to the vehicle. Ideally, the controller should be unable to distinguish between vehicle and laboratory operation. Thus, a controller should receive the expected inputs (e.g., commanded throttle position, wheel speeds) necessary for normal operation, while also delivering the required outputs (e.g., fuel injectors, transmission force motor). As shown in Fig. 5, the powertrain simulation (PSI), antilock brake (ABI), and motor load (MLI) interfaces provide the electrical transitions needed to connect controllers to the I/O rack.

The PSI contains circuitry designed to accommodate engine and transmission controllers, while the ABI electronics are targeted for chassis controllers. The PSI and ABI perform three types of operations on the I/O signals that pass between the controller and the RTS: analog and digital signal conditioning, the conversion of signals to different formats, and interconnection without modifying the signal. The first type of operation, signal conditioning, is applied to outputs from the controller (e.g., high-side drivers) or the RTS (e.g., low-side switches). An example of the second type of operation is the conversion of a pulse width modulated controller output to a voltage proportional to its duty cycle. In the third category, circuits pass select unconditioned controller signals (e.g., serial data) to an output port. An important consideration for the circuits in the first two categories is the provision of electrical loads equivalent to those found in an actual vehicle. However, these electrical loads cannot be easily adjusted to permit the introduction of signal shorting or noise disturbances. Consequently, a failure mode interface (FMI) has been designed. An attractive feature of the PSI is the ability to select between a front panel or RTS automated mode of operation to control the generation of signals. The user may either drive the HIL simulation by manually manipulating the simulator's switches and potentiometers, or place it under computer supervision (Section IV-A) to execute a test profile composed of driver commands.

The MLI provides an electrical load and interface circuitry between ABS VI controllers and the simulator. The electro-hydraulic ABS VI modulator regulates brake pressure in each channel (left front, right front, and rear) using a dc motor attached to a power screw which extends/retracts a piston to push/pull brake fluid. The MLI allows the simulator to exercise the controller's software in a realistic manner while applying reasonable electrical loads to the controller's hardware. This interface uses a static resistor-inductor (RL) network to load the motor driver circuits thus permitting the controller to realize its commanded motor current. During a simulation, the commanded motor current i_c is measured by the MLI and provided as input $\hat{i}_c$ to the motor driver model executing on the simulation computer (refer to Fig. 6). This model is coupled with descriptions of the dc motor, ABS modulator, and vehicle to calculate the estimated "actual" motor current $\hat{i}_a$, as well as the brake pressure and the chassis' response. To accept the "actual" motor current feedback signal from the simulator, rather than from the on-board motor driver circuit, the controller hardware must be modified (i.e., cut and jump). The MLI's approach to simulating dc motor loads through the use of static loads on the driver circuits and hardware-intrusive feedback avoids the difficulties associated with emulating the back-emf in hardware while retaining the effects of a dynamic load on the controller.

The FMI provides a computer supervised method for the hardware-based manipulation of the controller I/O. This instrument is positioned between the three hardware interfaces and the controller so as to modify the cable harness signals. The FMI provides two basic operations—signal shorting and signal summation. The signal shorting circuit offers four options for an input signal C: closed circuit, open circuit, short to ground,

and short to battery. The signal summation circuit introduces four capabilities for two input signals, A and B: closed and open circuits for A, replacement of A with B, and signal summation (A+B). An important feature of this instrument is the ability to automate its operation. High-level software directives may be specified in scheduler files to regulate each circuit, as well as to generate the additive or auxiliary signal B.

B. Controller Instrumentation

The Modular Development System (MDS) has been developed by Delco Electronics to support software testing and calibration activities. This instrumentation provides three primary capabilities when connected to a controller: emulation of program and data memories, high-speed data acquisition, and internal data logging. A personal computer (PC) provides the interface between the user and the MDS. The PC uses PC/NFS software to access the ethernet and permit remote operation of the instrumentation. The architecture of MDS enables the instrumentation's RAM, which emulates the controller's ROM, to be asserted in the controller's address space. Thus, the PC to MDS path allows the transfer of files (e.g. program code, calibration sets) to the instrumentation, thereby providing an alternative to programming controller memory devices (e.g., EPROMS).

The high-speed data acquisition and internal data logging capabilities of MDS are important tools for software development. By overlaying the controller's RAM with instrumentation RAM, the MDS captures data from the controller without disturbing its operation. The data is logged to a 4 MB RAM buffer in the computer interface buffer with internal logging (CIBIL). To synchronize flight recording operations for multiple data acquisition systems, an external triggered input and a system triggered output are available. During a test, the preselected controller variables are logged, processed, stored in RAM, and displayed on the PC or vacuum fluorescent display unit. At the conclusion of the test, this information may be transferred from the CIBIL to the Sun workstation.

IV. Automating the Controller Test Process

The development of software utilities to automate the controller testing process enhances the attractiveness of simulation tools. A computer supervised scheduler enables the controller inputs and simulation events to be prescribed in a repeatable manner through script files. To record the controller's response to this stimuli, data is logged from both the simulator and controller with the integrated data acquisition scheme (Section IV-B). Several test methods have been developed to facilitate the systems level verification and validation of integrated controller hardware and software.

A. Scheduler Utility and Test Scripts

The scheduler utility has been developed to schedule specific events (i.e., controller inputs, driving scenarios, and/or instrumentation operations) in a time indexed manner. This utility reads the user specified inputs or recorded in-vehicle test data from the designated scheduler file and, at the appropriate time instances, updates its outputs. A schedule file also contains information to direct the operation of the simulation environment and control the data acquisition process. Each file chronologically lists the simulation variables to manipulate, with their prescribed profiles, and the controller and RTS variables to be acquired through data acquisition. During execution of a simulation, the designated schedule file contents are loaded into the simulation and interpreted by the scheduler utility. The scheduled variables' signals are generated by the utility's software-based function generator (e.g., step, saw tooth) at the times specified for each variable.

To support a variety of driving profiles and test procedures, a number of schedule files must be created. In most instances, a schedule file is designed to verify one requirement in the test plan. Thus, a logical extension to the schedule file concept is the creation of test suites for systems and software verification. The grouping of these files into a series of test suites, perhaps organized by software functions or features, facilitates regression testing (i.e., selective retesting of a system to ensure that a software change has not caused unintended effects in another area). Ideally, the schedule files and test suites developed for one program will be directly applicable to future programs.

B. Integrated Data Acquisition

An integrated data acquisition strategy has been created to time synchronize the data from the controller instrumentation and the simulation computer (refer to Fig. 5). Controller hardware and software may be effectively investigated by analyzing the controller's internal variables, external I/O, and appropriate simulation variables. For instance, a split coefficient braking maneuver can be established using the scheduler utility. An ABS control algorithm's performance to this operating scenario may then be recorded and evaluated by logging controller data (e.g., estimated wheel slips) via the instrumentation, plus the vehicle dynamics (e.g., yaw angle) and controller I/O (e.g., wheel speeds) via the simulation computer.

The Sun workstation is the final destination for the RTS and MDS data. During a test, simulation data is continuously acquired through the RTS data acquisition utility and written to a workstation file. Meanwhile, controller variables are logged to the CIBIL and stored in RAM. In addition, the instrumentation sends synchronization signals to the RTS to be included with the simulation data. Once the test is completed, the MDS recorded information is transferred to the workstation and written to another file. These two data files are aligned and merged to create a single data file that documents the test.

C. Controller Test Strategies

The simulation facility provides a powerful tool for the verification (i.e., the process of evaluating a system to determine whether the products of a given development phase satisfy the requirements imposed at the start of that phase) of electronic controllers. Three strategies, labeled open-loop, closed-loop, and hybrid, have been developed for systems integration test-

ing [37]. The open-loop method directly provides specific input sequences to the controller using the scheduler utility. Normally, various automotive sensors provide these inputs based on the vehicle's powertrain and chassis dynamic behavior. Therefore, this test strategy assumes that the vehicle's response may be neglected, compensated for, or characterized by the prescribed controller inputs in the script files. The closed-loop method accepts driver inputs and controller outputs through the hardware interfaces to calculate the automobile's behavior on the RTS. The advantage of this strategy resides in the dynamic coupling of the vehicle dynamics and electronic controller to create an environment similar to the actual vehicle. Appropriate analytical and empirical models may be selected from the simulation library to create a suitable dynamic environment. The closed-loop scheduler test files will contain driving profiles characterized by typical driver commands. Finally, the hybrid test method directly manipulates select controller inputs per the open-loop method, while a closed-loop operating scenario produces the remaining signals. This methodology is beneficial in cases where the complete set of controller inputs cannot be prescribed, and physical relationships must be relied on to generate the remaining inputs.

The simulation laboratory also provides an environment to support the design of control strategies and the validation of control systems. The stability, sensitivity, and robustness of proposed control schemes may be investigated by exercising the algorithms in a closed-loop manner on the simulation computer without hardware. Control systems may also be validated (i.e., the process of evaluating a system at the end of the development process to determine whether it satisfies the overall systems functional requirements) in this laboratory environment. However, the correlation of the results with vehicle test data will depend on the accuracy of the various system models, as well as the emulation of the actuators and sensors. Thus, HIL tools should be viewed as a supplement to experimental testing.

V. Application of the Hardware-in-the-Loop Simulation Tool Set

Experimental and simulation results are discussed to provide insight into the underlying system dynamics and application of the tool set. Multiple ABS controller variables will be presented for an in-vehicle ABS stop, a HIL laboratory simulation of the ABS maneuver, and the HIL verification of a representative system software requirement. The in-vehicle experimental ABS testing was performed in a Saturn SL2 sedan. A description of the antilock brake control system's operation and components may be found in the Saturn service manual [43]. A number of tests were completed for various road surfaces and vehicle speeds; an ABS stop on dry asphalt will be presented. The vehicle was traveling at a speed of $V = 55.0$ MPH on a straight course when the brakes were applied at $t_b = 11.70$ s. The data collected was limited to the controller variables and status bits available through the data logger on the MDS instrumentation. In Fig. 7, the brake switch, right front (RF) wheel speed (in MPH), commanded RF solenoid

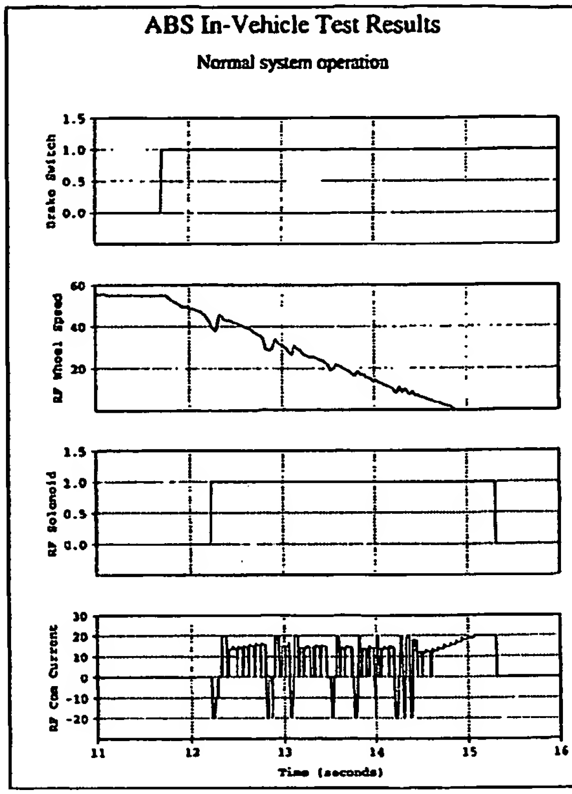

Fig. 7. In-vehicle ABS maneuver.

valve state, and RF commanded current (in amperes) are displayed. The discrete signals indicate inactive (open) and active (closed) states when the brake switch (solenoid lines) have a magnitude equal to zero and unity, respectively. For convenience, the data is presented between 11.0 s and 16.0 s to highlight the ABS stop. In this test sequence, the road conditions could not be rigidly controlled which resulted in varying surface texture (i.e., no type of uniformity can be guaranteed), irregularities, and presence of small debris (i.e., stones, gravel, etc.). Therefore, it will not be possible to rigidly match the simulation results to this road surface due to these nonlinear effects.

A HIL simulation was created to support software verification at the systems level for the ABS controllers. During the tool set development phase, the agreement between the in-vehicle and the laboratory simulation results was investigated. The appropriate brake modulator, vehicle, and tire/road interface parameter databases were loaded into the model-based simulation. Operating scenarios were created in the laboratory similar to those performed in the field. The scheduler utility permitted the repeatable simulation of a vehicle traveling at approximately $V = 55$ MPH with the brakes applied at $t_b = 11.70$ s. The MDS data logger acquired the same set of controller variables and status bits (refer to Fig. 8). To compare the in-vehicle and HIL simulated ABS test results, several characteristics (e.g., total stopping time, wheel speed profile, and commanded current features) will be examined.

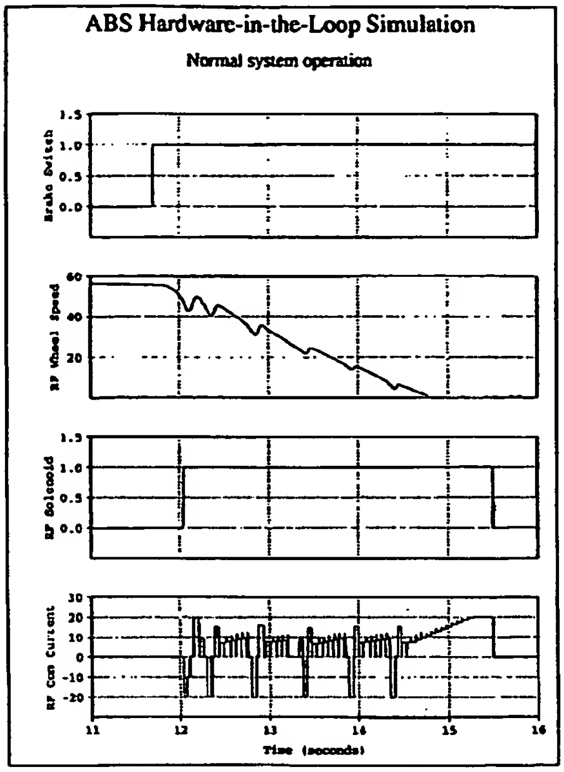

Fig. 8. Hardware-in-the-loop simulation of the ABS maneuver.

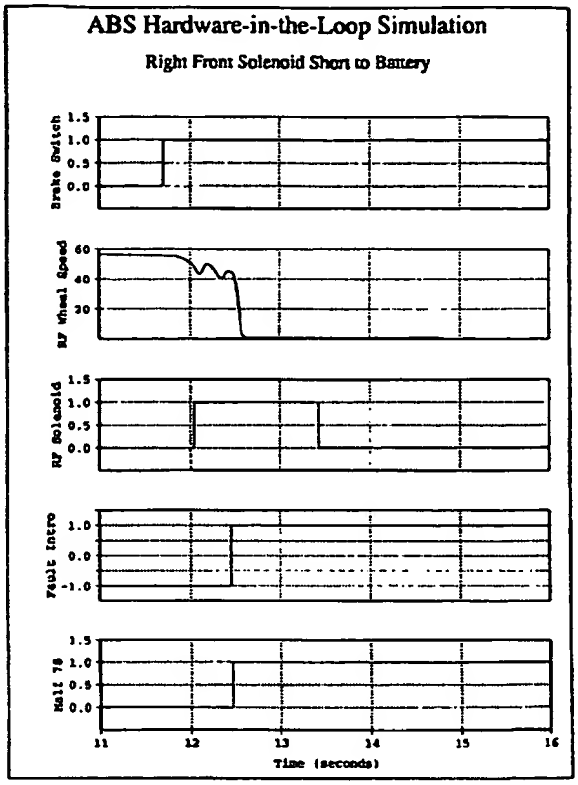

Fig. 9. Hardware-in-the-loop verification of an ABS controller diagnostic.

The elapsed stopping times for the in-vehicle and simulated RF wheels are 3.16 s and 3.07 s, respectively. Note that the wheel deceleration is approximately 26.0 (ft/s^2) or 0.8 g's for the given road surface. The number of impending wheel lockup and recovery events is approximately six for each case. However, the in-vehicle data also contains a number of minor departures, absent from the simulated results, which may be partially attributed to nonlinear effects and high-frequency unmodeled dynamics. The commanded current profiles for the initial ABS release and apply are similar in magnitude and duration for each case. The subsequent apply and release events differ between the in-vehicle and bench results due to the nonlinear and unmodeled dynamics, and the use of a different software calibration database which varied the magnitude of the incremental commanded motor current. Overall, the simulation results agree favorably with the in-vehicle test results.

To provide insight into the application of the tool, a short to battery diagnostic fault [43] will be verified for the RF hydraulic bypass solenoid. During an ABS maneuver, the controller provides battery voltage to close the solenoid valve and isolate the brake pedal input. Shorting the RF solenoid to battery voltage should cause the controller hardware to set a fault bit which results in the software disabling of the ABS modulator, setting diagnostic code 78, and illuminating the ABS telltale light. To verify the diagnostic, a scheduler file was created to introduce this fault via the FMI's signal shorting circuitry. The controller's variables, as well as the commanded FMI introduced fault, were recorded during the simulation. In Fig. 9, the brake switch, RF wheel speed, RF solenoid valve state, FMI short to battery status (inactive when the magnitude is -1), and malfunction 78 flag are presented. The introduction of a RF solenoid short to ground at $t_{fail} = 12.45$ s during braking results in the immediate disabling of the ABS system and setting of malfunction code 78.

VI. Observations

A number of observations have been made during the development and application of simulation tool sets at Delco Electronics. The comments are restricted to simulator requirements, system hardware/software, and the establishment of metrics. Although these categories are not exhaustive, they include issues that should be considered early in the development process.

A. Simulator Requirements

A comprehensive set of requirements is essential to identify and develop appropriate solutions to meet the simulation needs. A variety of simulation products exist ranging from PC's with plug in cards to powerful simulation computers with extensive I/O functions based on VMEbus architecture. Clearly, sophisticated models will require a simulator with sufficient compute power to calculate the dynamics in the

allotted time period. Further, a simulator should be viewed as an integral part of the computer aided engineering process with provisions for rapid prototyping.

B. System Hardware/Software

The hardware interface represents one of the larger expenses incurred when developing a simulator. Although vendors now offer a variety of interface circuits, the electronic functionality required by an application may not be available. Consequentially, the cost of in-house development (e.g., materials and engineering time) or the procurement of commercial solutions must be included in the budget. When designing an interface, a building block approach with software reconfigurable circuits is recommended.

Software maintenance is a continual task during the life cycle of the simulator. A large programming effort will be required to create the simulator's software utilities during the development phase. To apply the tool set, appropriate system models with the required databases should be available on-line. In most instances, modifications to the application software will be regularly requested to facilitate testing.

C. Establishment of Metrics

Often the application of sophisticated technologies to the product development process must be justified by quantifying the cost savings. To measure the direct and indirect benefits of a simulation capability on product design and testing, appropriate metrics must be established. Some measurable quantities that may be selected include changes in manpower requirements, level of experimental or in-vehicle testing, and warranty return rates.

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Design and Implementation of HIL Simulators for Powertrain Control System Software Development

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Abstract

There is considerable interest in the automotive industry in computer aided engineering tools that support rapid development of quality products. In this paper, we describe some of the design and implementation issues for such a tool, namely, a Hardware-in-the-Loop (HIL) simulator, in the context of powertrain control system software development. This HIL system is used to verify the production powertrain controller module (PCM) performance. Hence, the powertrain and driveline dynamics are simulated on the HIL hardware and the production PCM is the "hardware" in the loop. HIL system requirements from the users' and the system developer's perspectives are described. The paper focuses on important HIL issues related to the real-time powertrain models and the hardware signal interfaces.

1. Introduction

Automotive engineers are being challenged to deliver higher quality products faster with ever shrinking resources for global markets with disparate emission regulations and customer expectations. The design and implementation of control algorithms is a crucial element in the development of powertrains to meet these requirements. Ad-hoc heuristic design and implementation methods are being replaced by systematic, requirements driven processes. Vehicle requirements are cascaded down to powertrain system requirements which in turn generate individual engine and transmission subsystem requirements. The goal of the powertrain control system development process is to generate a production quality control system that will be calibrated by system engineers to meet powertrain and vehicle requirements in different markets. Due to intense competitive pressures, the development times are being shortened considerably. The goals of delivering a quality product with reduced "time to market" constraints cannot be successfully met unless modern computer aided tools are judiciously used in the development process. This paper describes some important issues in the design and development of one such tool used in powertrain control system software development.

Since the PCM hardware is often developed in parallel with the control algorithms and the vehicle subsystems, developers have little time to test and verify the control algorithm implementations. Currently, control systems are developed and tested using open loop testers and prototype vehicles. The final system validation (conformance to requirements) is also performed in prototype vehicles at various geographical locations to ensure that the controller algorithms are robust. Open loop testers have limited functionality for software testing since the developer cannot simulate the overall system feedback loops (e.g., resulting engine torque and speed as a function of changes in spark advance and fuel injected). If a "virtual vehicle" were available, a significant part of software verification and system validation could be completed in a laboratory environment.

Hardware-in-the-Loop (HIL) simulation systems provide such a "virtual vehicle" for system validation and verification. Different HIL configurations have been described in the literature for different user applications [1,4] based on the "hardware" that is "in the loop". The specific HIL system described here includes the powertrain control module (PCM) in the loop, while the powertrain dynamics, the sensor and actuator behaviors are simulated in the computing platform and interface circuitry. The PCM "thinks" it is in a car, and this allows engineers to validate the control system behavior in a "virtual vehicle" environment. In addition, the controller behavior can be validated at various environmental conditions and the controller robustness can be tested by introducing powertrain component and subsystem malfunctions. While a HIL simulator will not obviate the need for traditional test methods, it does allow developers to test the system in a repeatable laboratory environment. As a result, developers can identify and resolve problems earlier in the development cycle.

As with any system development, the design of HIL systems should be driven by requirements. Some of these high level requirements are described in the next section. There are several hardware and software issues that are important for a successful HIL implementation.

This paper is focused on those related to real-time powertrain modeling and signal interfacing and conditioning. A majority of the system design activity involves sorting out these issues and therefore merits detailed discussion.

2. Requirements for the HIL System

Since system requirements drive the design and influence trade-offs, careful attention has been paid to the task of collecting requirements. Requirements can be categorized as those from the end user and those relating to system development and maintenance. Along with these requirements, the available resources and system costs will significantly impact the design of the system. Some of the high level requirements are generic and are independent of the specific powertrain application. These include:

1. The system should be flexible so that it can be used in multiple applications with minimal changes.
2. The system should have sufficient fidelity so that controller malfunctions are only triggered under the same conditions as in the vehicle.
3. System debugging tools should be available to aid the end user as well as the system developers.
4. The models should be implemented in an easy to use environment that permits reuse and exchange of component models between architectures.
5. The computational platform should be expandable to permit future growth without adversely affecting the real time throughput of the system.
6. Use of commercial input/output cards with minimal customization is desirable.
7. Hardware and software interfaces should be "user-friendly" so that the end user is comfortable using the system.
8. A modular interface to the controller's physical signals is necessary to enable cost effective modifications, when required.

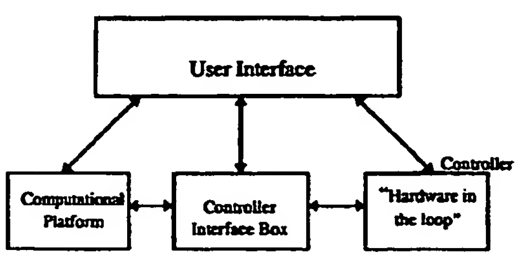

Figure 1: HIL System Components

3. Configuring and Implementing an HIL System

Besides the generic requirements described above, there may be application specific system requirements. All of these requirements should be taken into account in the HIL design and implementation process. A block diagram representation of the HIL system is shown in Figure 1. The following key process steps are involved in developing such a system:

- Identify the specific PCM expectations.
- Identify the HIL computational platform.
- Identify the modeling tool and generate "HIL oriented powertrain system models".
- Identify, partition and implement interface signal transformations and electrical characteristics.
- Develop standard test suites
- Implement an appropriate hardware and software user interface

Although each of the aforementioned topics is important enough to warrant a thorough discussion, this paper focuses on two of those topics, namely, the "HIL oriented powertrain system models" and signal conditioning and interfacing.

4. HIL oriented Powertrain System Model

A large part of the HIL development effort is dedicated towards assembling a powertrain behavior model. This may involve modifying and adapting existing models as well as developing new models. The real-time simulation models share some unique properties that include:

- Models include sufficient dynamics to meet the requirements of the PCM, but are not detailed enough for design purposes.
- Systems are typically represented by algebraic or ordinary differential equations.
- Implicit equations or algebraic loops are not used in the models, because these representations require an iterative solution process and the real-time nature of HIL systems requires finite computation times.
- Fixed step size explicit schemes such as Euler, trapezoidal or Runge-Kutta methods are chosen as the integration algorithm.
- Unnecessary units or scaling conversions in the model are eliminated to reduce computational burden.

Typically, HIL system models are adapted from hardware or control system design models and are modified to conform to the above requirements. In addition, the models may be extended to react to user

triggered faults. The models have been developed in SIMULINK® and[1] STATEFLOW™.

4.1 Model Architecture Definition

One of the first steps in the modeling process is the development of a system model architecture. The model architecture defines and establishes the various functional units and the signal interface between the units in the model. During the architecture definition process, the structural decomposition of the model is also decided. At the root level, the model has been partitioned into User Inputs, Powertrain Systems, Actuators and Sensors. The Powertrain Systems unit is further partitioned into Engine, Driveline, Catalyst and Accessory Loads. Engine Sensors, Driveline Sensors and Accessory Loads Sensors make up the Sensors unit. Similarly, the Actuators model unit is partitioned into Engine Actuators, Driveline Actuators and Accessory Loads Actuators. The Actuators and Sensors are connected to Input and Output Hardware Interface units respectively. The Hardware Interface units consists of specific models of the I/O cards. These models are supplied by the platform provider and can be programmed easily from the standard SIMULINK® user interface. The User Inputs unit has all the model elements (including GUIs) for an interactive experiment session.

4.2. Model Description

Typical control oriented models provide adequate fidelity for control software validation. Modeling standards and rules regarding labeling, units, ranges and data types have been established and documented. These standards will be invaluable while using and updating the models. The models are discretized at a sample rate of 1 millisecond for the real-time implementation. A brief description of the important sub-models follows.

Engine: This simulation model generates key variables such as engine speed, brake torque, intake and exhaust manifold pressures, mass air flow through the engine, air-fuel ratio of the combustion mixture and exhaust temperature and emissions. Modeled subsystems include intake manifold dynamics, fuel wall wetting, engine breathing, intake to powerstroke delay, torque generation, exhaust temperature and pressure dynamics and feedgas emissions [2,5,7].

Driveline: The driveline simulation includes models of the torque converter, transmission and the driveline dynamics. The torque converter model, which consists of algebraic relationship between pump and turbine torques and their rotational speeds, provides the load torque to the engine and torque to the downstream components. The drive shaft dynamics models the shaft torque and turbine speed as a function of the turbine torque and driven wheel speed. The driveline inertia is lumped into single inertia elements for each of the gears in this model. The longitudinal dynamics model calculates the vehicle and wheel speeds.

Catalyst: A three way catalyst model emulates the behavior of the exhaust after-treatment system. Key elements include an oxygen storage model, catalyst efficiency model and a catalyst warm-up model [3].

Accessory Loads: Accessories such as air conditioner clutch and a power steering pump are modeled to generate appropriate loads on the engine crankshaft so that realistic engine cranking and start up behaviors are simulated.

Actuators and Sensors: The actuators and sensors are the key elements in the model architecture and transform physical quantities into electrical signals required by the PCM. The actuator and sensor electronics can be simulated either in the interface hardware or in the SIMULINK® environment. The mechanical elements of the sensors and actuators are modeled in SIMULINK®. The mechanical behaviors are typically represented as static nonlinear functions and lags or delays. The effect of malfunctions, introduced by the user through either the hardware or the software interface are also modeled.

4.3. Flexible Modeling Environment

An important system requirement is the ability to change individual model elements rapidly between experiments. This provides the users with the capability of using varying levels of component model complexity to debug an undesirable behavior in a system. The problem area can be isolated first by choosing simple subsystem models and complex models can be used subsequently to perform root cause analysis of the problem. An user friendly modeling environment based on the SIMULINK® library concept has been developed to support reusability and flexibility [6]. The use of this environment has significantly reduced the time to reconfigure models for various applications. Additionaly, using a library source to implement a model that is used multiple times leads to ease of maintenance of the model architecture.

5. Signal Interfacing and Conditioning

The identification and implementation of the interface between the computing platform and PCM is extremely important and very time consuming. Issues related to Signal Transformations, Physical Signal Interfacing and

[1] SIMULINK is a registered trademark and STATEFLOW is a trademark of The Mathworks Inc, 24 Prime Park Way, Natick, MA 01760

simulation of I/O Hardware Fault Conditions have to be sorted out. An in-depth knowledge of the PCM circuitry and capabilities of the computational platform is necessary to address these issues.

5.1. Transformation Of Signals

An HIL environment requires signals from the computational platform to be interfaced to the hardware in the loop. Hence, signal transformations from the physical (electrical) domain to engineering units are required. As an example, engine fuel injector commands are electrical pulses to a solenoid, but result in a fuel mass flow rate in the model. Generally, the hardware interface signal behavior can be generated in one of several ways:

1. Simulation output on the computing platform
2. Output of an input-output signal processor card
3. Output of the custom signal conditioning boxes
4. Output of a custom hardware circuitry.

During the design phase, one must decide on the proper partitioning of signal processing into available software and hardware. This results in a trade-off between system complexity, computational burden and maintainability. By moving functionality from the models to the hardware interface, the computational burden is decreased. This will free up computational resources to meet the real-time target. However, the hardware interface may become more complex and may require additional resources to maintain it. In the case of the fuel injector example, the primary task is to measure the duration of pulses commanded by the PCM when the injectors are open. This task is completed in several steps. The duration must be measured with reference to the crankshaft angular position. There may also be an arbitrary number of additional pulses to be measured within a finite angular position of the engine (e.g. 720 degrees of crank revolution). All of these pulses must be summed to represent a total fuel flow commanded by the PCM into individual cylinders of the engine. To implement the primary task, a designer must choose to either let the computational platform measure the pulses and generate the rate of fuel flow into the engine cylinders, or the hardware may be intelligently designed to measure this fuel flow and provide this as a scaled engineering unit value to the computational platform.

Another way to resolve the signal transformation issue is to have each of several processors in the computational platform dedicated to specific tasks. The core plant model could be executed in a set of dedicated processors while the I/O functionality could be partitioned among several other processors.

5.2. Physical Signal Interfacing

The current state of the art in automotive powertrain control technology demands that PCMs interface with a wide range of sensors and actuators. It is common to see a PCM with 100 to 160 I/O pins and the HIL system must provide valid interface for each of these pins.

Powertrain controllers typically contain many types of output circuits depending on the automotive application. These include low side and high side driven lamps, solenoids, and motors. There are also requirements for current controlled devices such as current controlled solenoids and high current - high pressure solenoids. Controller inputs are differential variable reluctance sensors (VRS), switch inputs pulled up or down within the controller, Hall effect signals, and analog voltages from pressure and temperature sensors. The following points are important when designing the HIL interfaces to these types of signals:

1. Some solenoid or current controlled driver circuits require feedback. For example, some drivers require a load inductance because they use switching circuits to control the current. In other cases, the flyback voltage from an inductive actuator may be used to perform diagnostics on the actuator. These special cases must be accommodated by the HIL system to prevent unintentional fault conditions from being detected.
2. In many cases, current sensor technology provides simple analog voltage outputs for temperatures and pressures. In most cases, these signals may be simulated by using digital to analog (DAC) drivers in the HIL system.
3. Where possible, the HIL system should utilize some form of arbitrary waveform generation for VRS signals. This will allow users to simulate fault conditions for these signals.
4. The interfacing requirements of the driver circuitry within the PCM needs to be understood. In many cases, output loads can be simulated with simple resistive loads as long as the normal operating currents are preserved for the driver circuits.
5. Key elements in the simulated load circuitry should be easy to modify. Sockets for resistive loads, separation of solenoids or inductors into functional 'packs' (e.g. simulated fuel injector inductors) that can be swapped are two examples of how this will be accomplished. This will ensure that the HIL system can accommodate as many controller applications as possible.

To illustrate some of the points described above, an implementation of a simple resistive low side driven actuator is shown in Figure 2. In this case, the fault simulation block (see Section 5.3), voltage level conversion, and noise immunity may reside in one system enclosure. The load, Rload, may reside in a separate load simulation enclosure with other simulated actuators, and the HIL system I/O hardware may be another enclosure which utilizes commercially available hardware (e.g. timer/counter capture circuits, A/D circuits, DAC circuits, arbitrary waveform generators, etc.).

5.3. Signal Fault Simulation

Automotive powertrain controllers utilize many intelligent integrated circuits for driving actuators and monitoring sensor outputs. This intelligence is necessary to accomplish self diagnosis of fault conditions. In many cases, these diagnostics must be executed during normal operation of the PCM software. PCM software verification requires that the software be tested under normal and abnormal modes. Since the abnormal modes of operation are tested under control, the HIL system must have the ability to force fault conditions for appropriate controller signals under automatic control. Typical fault conditions encountered in automotive environments are listed below:

1. Short to ground - A controller signal has been short circuited to ground.
2. Short to battery voltage - A controller signal has a low resistance path to vehicle battery voltage.
3. Open circuit - A controller signal has no path to ground.
4. Shorted load - A controller actuator has been shorted to ground (the difference between this and a short to ground is whether an actuator is driven from the high side or low side).

In Figure 2, the Fault Simulation block shows a method of implementing fault generation in a HIL system. In this case, fault simulation is the last layer of hardware interface to the PCM signal. The fault simulation is accomplished through a series of relays which may be controlled by the HIL simulator. These relays will alternately switch the PCM signal to either of the fault conditions or complete the signal path to the HIL simulator.

6. Conclusions

The task of putting together a flexible HIL system for verification of production PCM performance is significant. In this paper, we have addressed two important HIL system aspects related to the real-time models and the hardware signal interface. Based on our experience, these two issues require a great deal of attention in the early stages of development and are critical to the success of HIL based product verification. Implementing the real-time model infrastructure involves structure identification, parametrization and validation. The model structure has been described here. Parametrization and validation procedures are resource intensive and require extensive powertrain data. This will be the subject of a future publication. Hardware signal interfacing and conditioning is a very complex and time consuming activity. Having a good signal interface design and implementation will result in a well controlled system test. This paper has identified several critical factors needed to achieve a robust signal interface to the PCM. Further details on the HIL system along with the results of HIL based testing will be reported in a separate paper.

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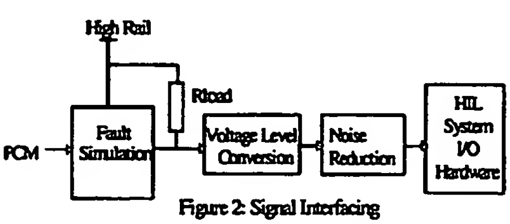

Figure 2: Signal Interfacing

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